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A MONTHLY PRECIPITATION AMOUNT CLIMATOLOGY DERIVED FROM PUBLISHED ATLAS MAPS: DEVELOPMENT OF A DIGITAL DATABASE

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1. INTRODUCTION

A significant predictor input to the Local AWIPS MOS Program (LAMP) quantitative precipitation forecast (QPF) product is expected to be a localized precipitation amount climatology. One available climatology, described in Charba (1992), is based on a 27-year archive of the QPF predictand. While this climatic input is expected to be effective as a local QPF predictor, it has some limitations. One is that the density of points that underlie the gridded climatic frequency analysis is sparse in some parts of the United States, particularly in the intermountain West. Another drawback is that since the regression equations (which form the basis of the QPF's) will be derived from a subset of the sample used to develop the climatology, an excessive correlation between this climatic predictor and the predictand is possible. Because of both of these considerations, the predictand climatology had to be subjected to extensive smoothing. An undesirable consequence is that resolvable temporal and spatial detail in some areas was lost. For these reasons, it was thought that an independently-derived precipitation climatology that contains fine spatial detail could serve as a useful supplement.

An independently-produced monthly precipitation amount climatology that contains the desired properties was available in the form of graphic atlas maps from a study by Miller and Frederick (1966). This note describes these maps, and a graphics-to-grid interpolation procedure used to derive a digital data set from them. The digital data set consists of grid point values of these climatic frequencies on the 20-km QPF predictor/predictand grid (Fig. 1). The paper concludes with a few comments on how the data set will be used as a climatic predictor in the QPF technique under development.

2. CLIMATIC ATLAS MAPS

The atlas maps consist of contours of the average number of 24-h periods per month with precipitation ≥ 0.50, ≥ 1.00, ≥ 2.00, and ≥ 4.00 inches at a point. As discussed by Miller and Frederick (1966), the mean number of 24-h periods per month with precipitation meeting these thresholds was computed from daily precipitation observations taken at a fixed time of the day. The basis for the computation was the formulation of empirically-derived ratios between the number of 24-h periods per month with a threshold precipitation amount and the corresponding number of days based on daily observations. The distinction between the two precipitation measurements making up the ratio is that the 24-h amounts are taken at the ending time of a rain event, while the daily amounts are measured at a specific time of the day. The ratios were 1.2 at the ≥ 0.50 inch threshold, 1.3 for ≥ 1.00 inches, and 1.4 for both ≥ 2.00 and ≥ 4.00 inches. Note that the number of 24-h periods per month meeting the thresholds is greater than the corresponding number of "observational days." This result arises because heavy precipitation events sometimes straddle two

observational days, with the consequence being that the amount does not reach the threshold on either day.

The number of stations over the conterminous United States for which the normal monthly number of 24-h periods were derived was 1240. However, for the ≥ 0.50 and ≥ 1.00 inch thresholds, the mean number of 24-h periods per month (henceforth called monthly frequency) for a subset of 556 of these stations was approximated from mean monthly precipitation amounts for the same stations. As before, a previously-derived empirical factor was used to estimate the monthly frequencies from the normal monthly amounts. Thus, for the ≥ 0.50 and ≥ 1.00 inch thresholds, the number of stations with explicitly computed monthly frequencies was only 684. This station total is about one-fourth the number used in climatic frequency analysis conducted by Charba (1992).

Miller and Frederick (1966) drew the monthly frequency contours subjectively on the basis of plotted station values. To compensate for the relatively small number of data points, the authors incorporated additional information into the subjective analysis in order to enhance the spatial detail. For instance, they incorporated the complex effects of orography, and meteorological factors such as moisture sources, wind flow patterns, exposure, etc. into the contour patterns. The additional spatial detail in the contour patterns made possible by the added information was considerable in areas of rugged mountainous terrain. An example map is shown in Fig. 2.

3. TRANSFORMATION OF GRAPHIC MAPS TO GRID POINT FIELDS

The development of the digital database, consisting of the monthly frequencies from the atlas maps at each of the 19,636 points of the analysis grid (Fig.1), is a problem which falls in the category of graphics-to-grid interpolation. The solution to the problem involved two tasks. The first task involved digitizing each contoured map, i.e., extracting points along each contour, and mapping these points onto the analysis grid. The subsequent task involved interpolating from the digitized points to the grid points. This pair of tasks was required for each of 36 atlas maps, 12 monthly maps for each of three threshold precipitation amounts (≥ 0.50, ≥ 1.00, and ≥ 2.00 inches). The ≥ 4.00 inch maps were not processed because of their characteristic scarcity of contours.

A. Digitization of the Atlas Maps

The digitization of a map was performed through use of a digitizing table together with a commercial software package called AUTOCAD. The process was performed by first positioning a map on the table, and then registering its dimensions in rectangular map coordinates. The map registration included specification of the map coordinates of two points of known latitude and longitude. The latter is required for the transformation of the extracted points in rectangular map coordinates to earth (latitude/longitude) coordinates.

The digitizing process consisted of positioning a cursor on a contour and manually sampling points along it. It should be noted that, as an alternative, the AUTOCAD software supports automatic sampling of points for a selected incremental distance along the contour. We chose the manual option because less subsequent editing was needed.

Following initial digitization of a given map, the extracted points were checked for digitizing errors. The first step in this quality control check consisted of connecting points along contours with straight line segments, and then, with a machine plotter, plotting all contours on paper charts at the same scale as the original atlas maps. The second step consisted of superimposing the plotted map on the original, and then carefully viewing the match-up for any discrepancies. Uncovered errors were readily corrected through use of the editing feature of the AUTOCAD software.

B. Mapping of Digitized Points

The map base used for the atlas maps is an Albers Equal Area projection. Using transformation equations given in Pearson (1990), software was developed to convert the positions of the digitized points from map coordinates to earth coordinates. A subsequent comparison of the computed latitude-longitude values for map points with known values revealed a systematic error of up to 0.5 degrees latitude and 0.2 degrees longitude. Since the source of the problem in the transformation procedure could not be determined, we removed the error by means of an empirical correction to the computed values. The empirical correction was performed by evaluating the error at known latitude-longitude intersections spanning the map, and then applying correction values at all digitized points.

The corrected latitude-longitude points were subsequently mapped onto the analysis grid (Fig. 1), which is a polar stereographic projection. For example, Fig. 3 shows a mapping of the digitized contours from the atlas map in Fig. 2 on the analysis grid map base. The subsequent interpolation of the climatic frequencies from the irregularly-spaced point values along the contours to grid points is considered in the next section.

C. Procedures for Interpolation to Grid Points

The interpolation from the field of digitized points to grid points was a challenging problem, for several reasons. One is that simple interpolation schemes, such as those based on one-dimensional curve fitting, are not applicable because the spacing of the digitized points is highly irregular. In fact, the non-randomness of the data spacing would inevitably result in poor performance even with more elaborate interpolation procedures (e.g., those based on two-dimensional curve fitting, or sucessive correction objective analysis) that are applicable for randomly distributed data. As can be seen from Fig. 3, the data distribution in some locations of the map is extremely irregular. For instance, in localized areas of the central and northern High Plains and outside the borders of the United States, data appear to one side of a given point but not to the opposite side. For such locations, the interpolation problem becomes one of extrapolation, which, at best, is risky for any analysis scheme.

A search was conducted within the meteorological community for previous efforts to treat such a graphics-to-grid interpolation problem. Since the search did not yield a proven technique, we pursued a course to apply an objective analysis method commonly applied for randomly spaced data. The technique is a modified version of the objective analysis applied by Cressman (1959). However, because of the high irregularity of the digitized data it was recognized that either the analysis technique or the digitizing

procedure (or both) would likely require enhancements or adaptation in order to achieve a satisfactory interpolation.

The particular version of the Cressman method is quite similar to that described by Glahn et al. (1985), with minor differences. One difference was in the specification of the scanning radii. Instead of a pre-specified (fixed) set, the scanning radii were prescribed to be a function of the average spacing of the digitized points over the data rich region of the analysis grid. Another difference involved the algorithm for smoothing between passes; instead of the five-point weighted average applied by Glahn et al. (1985), we used a nine-point weighted average (Shuman, 1957). Also, we did not apply error checking procedures to the input data (which is common with the Cressman method) because the manual quality control check noted above was believed sufficient. Finally, we should add that the analysis grid consisted of a 175 x 220 rectangular array with a mesh size of about 20 km (Fig. 1).

The initial attempt of the analysis was performed on the basis of the Cressman analysis method and the digitization of the atlas maps, both as described above. Not surprisingly, the results were less than satisfactory. For illustration, Fig. 4 shows a contoured representation of the gridpoint analysis based on the digitized data plot given in Fig. 3. A comparison of the analyzed contours (Fig. 4) with the original ones (Fig. 2) reveals a number of analysis errors. Note in Fig. 4 the misanalyzed small, closed contours in northeastern Alabama and central Tennessee and the gross distortion of the 2.0 contour around Mississippi. Also, note the error in the extrapolation of the contour gradient near the coasts of North Carolina, South Carolina, Washington, and California.

To alleviate the analysis deficiencies, enhancements were applied to both the digitizing process and the Cressman analysis technique. One enhancement to the digitization involved sketching additional contours on the original maps in areas where the spacing was excessive, and subsequently adding the new contours to the digitized data set. The sketching of new contours involved subjective interpolation between existing contours, i.e., there was no attempt to incorporate additional information into the original maps. Another digitizing enhancement consisted of mathmetical interpolation of additional points between the digitized points where the spacing was more than 30 km. The intent of the interpolation was simply to increase the number of data points. The increase in data count achieved per digitized map (due to the interpolation) was substantial. For instance, the number of original digitized points per map was in the range 1000-3500, and the number of new interpolated points per map was in the range of 800-1500. To illustrate both digitizing enhancements, Fig. 5 shows the data plot given in Fig. 3 following the addition of the sketched-in contours and the interpolated points. Note that, primarily because of the new digitized contours, the data distribution is much more uniform than it was before.

The enhancement to Cressman analysis method involved an adjustment to the successive correction scheme. With the conventional correction scheme, the

corrected estimate of the analysis, ϕ'', at grid point (j,k) is related to the previous estimate, $\phi'_{j,k}$, by

$$\phi''_{j,k} = \phi'_{j,k} + \frac{\sum_{i=1}^{N} w_i (O_i - \phi'_i)}{\sum_{i=1}^{N} w_i}, \qquad (1)$$

where O_i is the observed or "true" value of ϕ at the point i, and ϕ'_i is an interpolated value of ϕ' at the same point. In (1), the weight, w_i, applied to the difference between O_i and ϕ_i', is given by

$$w_i = (R^2 - d_i^2)/(R^2 + d_i^2),$$

where R is the radius of influence about the grid point (j,k), and d_i is the distance from (j,k) to the point i. In the present application, O_i in (1) corresponds to a digitized data point, and N is the number of these points within the circular influence area. The modification of (1) applied for the present study consisted of multiplying the correction term (second term on the right side) by an adjustment factor, $\gamma(r_c,R)$, such that (1) becomes

$$\phi''_{j,k} = \phi'_{j,k} + \gamma(r_c,R) \frac{\sum_{i=1}^{N} w_i (O_i - \phi'_i)}{\sum_{i=1}^{N} w_i}, \qquad (2)$$

where r_c is the magnitude of the vector from grid point (j,k) to the centroid position of all digitized points within the influence circle. The intended function of γ was to reduce the correction term in direct proportion to the degree of data asymmetry (as given by r_c) about the grid point. By design, γ was to lie in the range from 0.0 to 1.0, and it was to have high values for small r_c (little asymmetry) and low values for large r_c (high asymmetry). The functional form for γ was specified as

$$\gamma(r_c,R) = \alpha f(r_c,R) + \beta, \qquad (3)$$

where $f(r_c,R)$ was a prescribed mathmetical function. The function, f, which was selected based on experimental tests, was constrained to a range of 1.0 (for $r_c = 0.0$) to 0.0 (for $r_c = R$). Among the forms tested were linear, polynomial, trigonometric, and exponential. In (3), α and β are parameters that take on positive values and whose sum is 1.0 ($\alpha + \beta = 1.0$). (Actually, for the case in which an exponential function was specified for f, the sum of α and β was slightly less than 1.0. This result was returned when packaged software was used to fit γ to a prescribed set of points with the exponential function specified for f.) Note that for $\alpha = 1.0$, $\beta = 0.0$, and $f = 1.0$ (for all possible values of r_c), the adjusted Cressman correction scheme given by (2) reverts to the conventional scheme given by (1).

The adjusted Cressman correction scheme was subjected to extensive preliminary testing on the basis of a simulated field. The simulated field featured a simple trough-ridge pattern elongated in the north-south direction. The troughs and ridges exhibited sharp gradients, but plateau bands separated each of them. The simulated field was digitized in a manner similar to the digitization of the atlas maps. The testing was performed by applying the adjusted Cressman correction scheme defined by (2) and (3) with various choices for the function, f, and the parameters α and β, and evaluating the results for performance. On the basis of both objective and subjective performance measures, the γ function found to perform best was

$$\gamma(r_c, R) = 0.84\left(\frac{1}{1+e^{-10.27+\frac{20.54 r_c}{R}}}\right) + 0.13. \qquad (4)$$

With the correction adjustment provided by this function, the improvement in analysis performance over that resulting from the conventional Cressman correction procedure [$\gamma = 1.0$ in (2)] was found to be dramatic. Among the various functional forms of γ tested, the exponential [as exemplified by (4)] performed best, followed in order of decreasing performance by the trigonometric, polynomial, and linear forms. The conventional Cressman correction scheme performed poorest.

Surprisingly, when the adjusted Cressman scheme embodying (4) for γ was applied to actual digitized frequency fields, the analysis performance was found to be disappointing. The analyzed patterns, which are not reproduced here, were found to contain such undesirable properties as small erroneous closed contours and fine scale wiggles in some valid contours. In fact, even the unadjusted Cressman scheme produced a better analysis. The degradation in performance from that attained with the simulated field was deduced to occur because of a combination of factors that placed more stringent demands on the correction scheme. One factor was that the climatic frequency patterns exhibited much higher spatial complexity than the simulated field. Because of the increased complexity, the distribution of sampled data points for the frequency maps was much more irregular than that for the simulation. Thus, with the increased irregularity in the data distribution, the data asymmetry (r_c) values often exhibited large, incoherent changes from one neighboring grid point to another. Since the sensitivity of the correction to the value of r_c was strong, the spatial distribution of the correction term values in (2) tended to be chaotic. This resulted in an analysis with erroneous fine scale "noise."

Another type of analysis error that resulted from the strong reduction in the analysis correction in areas of high data asymmetry was that some grid points with large r_c values did not receive an adequate correction from the initial guess field. Since a good guess field was not available for this study--the mean value of the digitized points was used--this type of error was sometimes substantial. The error was observed most often near a grid border when the nearest digitized contours were far away, particularly when the distant contours intersected the grid border at large angles. However, this type of error occurred occasionally even for interior areas in locations where the data asymmetry was very large.

Following the development and testing of the adjusted Cressman correction scheme, it was discovered that in a previous study by Reap (1976) a similar adjustment for asymmetric data distributions had been applied successfully for the analysis of lower tropospheric temperature and dewpoint. Although the analysis scheme used in the Reap study was different from the Cressman successive corrections method, the concept of the adjustment of the data weighting to account for asymmetric data distributions was similar. The Reap application of the asymmetric data adjustment achieved greater success than that yielded here for at least two reasons. One was that the lower tropospheric thermal and moisture fields defined by the conventional sounding network have greater spatial regularity than the climatic frequency fields considered here. Another factor--which is believed to be the dominant one--arose from the fact that in Reap's application the analyzed value of temperature (or dewpoint) for a grid point was computed as a weighted combination of two good sources of temperature data. When the analysis, based on the primary source of information (radiosonde temperatures), was deemed unreliable due to asymmetric data coverage, greater relative weight was placed on a useful alternate data source, numerical model initialized temperatures. In the present application, the alternate information was provided by the guess field which, as noted previously, was quite poor. Consequently, a poor analysis in such areas was inevitable. Thus, a major problem encountered with the strong correction adjustment given by (2) and (4) was the unavailability of a good guess field.

Under the circumstances, we were forced to relax the strong adjustment to the Cressman correction scheme which was found most useful with the simulated field. In the relaxed scheme, the function, γ, took on the form

$$\gamma(r_c, R) = 0.4 \frac{1.0+\cos\frac{\pi r_c}{R}}{2.0} + 0.6. \qquad (5)$$

Note that with (5) the correction term in (2) is reduced at most by the factor of 0.4 (when $r_c = R$), whereas with (4) it could be reduced by a factor of as much as 0.87. Thus, (5) represents a much weaker correction adjustment. The relaxed adjustment was selected on the basis of experimental application on the enhanced digitized maps. In the experiments, subjective evaluations of performance indicated that the weak correction adjustment produced a slight improvement in the analysis over the unadjusted scheme. The degree of improvement is addressed further in the next sub-section.

D. Results with Enhanced Analysis Procedures

The enhanced analysis procedure, which includes the interpolation between digitized points, new sketched-in frequency contours, and the relaxed adjusted correction scheme, was applied to all 36 frequency maps. Fig. 6 illustrates the enhanced analysis for the example map shown in Figs. 2 and 5. The improvement obtained with the enhanced analysis can be seen by comparing Fig. 6 with Fig. 4, the latter figure being for the unadjusted Cressman correction scheme and non-enhanced digitization. Note that the analysis error inland of the Gulf Coast and along the Atlantic and Pacific Coasts in Fig. 4 does not appear in Fig. 6. Note further that the enhanced analysis does a good job of replicating the original atlas map (Fig. 2). The sole noticeable difference between the atlas map and the analyzed map is that the latter does

not fully resolve all the finest spatial detail seen in the former. (Note that the apparent smoothing in Fig. 6, particularly along the Continental Divide, is partly a figment resulting from the unequal contouring intervals used in Fig. 2.)

It should be noted that the improvement of the enhanced analysis over the unenhanced analysis resulted primarily from the addition of the sketched-in lines. This result can be seen by carefully comparing Fig. 6 with the corresponding analysis in which the only enhancement is the addition of the sketched-in lines (Fig. 7)--the latter does not include the analysis correction adjustment or interpolation between digitized points. Note that the analysis in Fig. 7 exhibits only minor degradation, primarily in the fine detail, relative to the analysis in Fig. 6. This implies that the remaining improvement due to the interpolation between points and the relaxed correction adjustment is small.

A significant question that remains is whether or not the relaxed correction adjustment contributed a worthwhile improvement to the analysis. Our subjective examination of many maps revealed that it consistently contributed a notable improvement in instances in which a discontinuity in the digitized frequency data was accompanied by a steep gradient oriented normal to the discontinuity. In such instances, the conventional Cressman correction scheme consistently extrapolates the gradient into the data void area, which is usually undesirable. The adjusted correction, even in its relaxed form, reduces this type of analysis error. A comparison of Fig. 6 with Fig. 7 illustrates the reduction of the extrapolation error. These two analyses were identical except that correction adjustment was used for Fig. 6 but not for Fig. 8. Note that the extrapolation error along the North Carolina, Washington, and California coasts in Fig. 8, manifested as a misplacement of peak frequencies slightly seaward of the respective coasts, is not evident in Fig. 6. Another finding revealed by our subjective examinations was that there was no evidence of analysis degradation that could be attributed to the correction adjustment. In fact, for areas where the data coverage was fairly uniform, the adjusted correction and conventional correction methods produced virtually identical analyses. A careful comparison of Fig. 6 with Fig. 8 also supports this finding. Thus, it was concluded that the relaxed adjustment produced a worthwhile, if small, improvement to the precipitation frequency analysis.

4. DIGITAL CLIMATIC DATABASE

The enhanced analysis procedure was applied to each of 36 atlas maps--12 months and three precipitation thresholds. For the sake of completeness, Figs. 9 and 10 illustrate the analyses for ≥ 0.50 and ≥ 2.00 inches, respectively, for the same month (December) previously illustrated for ≥ 1.00 inches (Fig. 6). Note that the contour patterns in Figs. 9 and 10 bear a strong general resemblance to those in Fig. 6, except that the magnitudes of the frequencies are larger for ≥ 0.50 inches and smaller at ≥ 2.00 inches. Note also, that the frequency pattern for ≥ 2.00 inches (Fig. 10) is essentially flat--near the zero level--over most of the United States outside the Gulf, lower-Atlantic, and Pacific Coast states. It is gratifying that the analysis procedure is able to faithfully resolve tight frequency gradients in areas where they appear, and yet not introduce analysis noise in locations where the field is flat.

For each of the 36 maps, the analyzed frequencies for the conterminous United States (all grid points shown in Fig. 1) were stored in an unformatted (binary) file on magnetic tape and computer disk volumes. Software for reading the file is available for external users.

5. SUMMARY, CONCLUSIONS, AND REMARKS

The development of a digital database consisting of gridded climatic precipitation frequencies from published atlas maps was a problem that falls in the class of graphics-to-grid interpolation. The problem faced in this study was formidable primarily because of the great geographical variability in spatial detail that characterized the atlas maps. The Cressman objective analysis method was applied to obtain the desired grid point values from fields of machine-digitized frequency contours. However, enhancements to the digitizing procedure and the analysis scheme were needed to achieve a satisfactory replication of the original contour patterns. The enhancements consisted of (1) adding sketched-in contours to the original contour patterns, (2) adding interpolated points between digitized points, and (3) the application of an adjustment to the Cressman correction scheme.

Test results indicated that, among the enhancements, the sketched-in contours contributed most toward achieving an acceptable analysis. However, the adjustment to the analysis correction scheme, which was developed for the present application, consistently improved the analysis for at least one common scenario that results in error with the unadjusted scheme. Furthermore, the correction adjustment appears to have potential for general improvement of the Cressman analysis method, particularly when a useful first guess of the analysis is available.

The correction adjustment, in effect, results in increased weighting of the guess field estimate of the analysis in areas of poor or asymmetric data coverage about the grid point of concern. Unfortunately, a good guess field was not available for the present application; thus, the level of the adjustment was necessarily set to be small. Consequently, the improvement to the analysis was also small. For other applications where a good guess field is available, the adjustment should be increased and the improvement to the analysis could be substantial.

The analysis achieved with the enhanced digitizing-analysis procedures produced a good replication of the atlas maps. The gridded fields are available in binary form for 36 maps for general usage. Our intended application involves using the frequencies as a local climatic predictor of precipitation amount in a statistical forecast technique. The frequencies should provide a useful predictor input, particularly in rugged mountainous areas where other predictor parameters are weak. However, one must bear in mind that the frequencies lack information concerning the diurnal variability of precipitation occurrence. With the planned statistical approach, this limitation will not be a factor so long as the data samples used for development of the statistical relationships are pooled within geographical areas where the frequencies exhibit similar diurnal properties. Another source of climatic precipitation frequency data, in which diurnal variations are resolved,' (Charba, 1992) will be used to determine the diurnally-homogeneous climatic regions.

6. ACKNOWLEDGEMENTS

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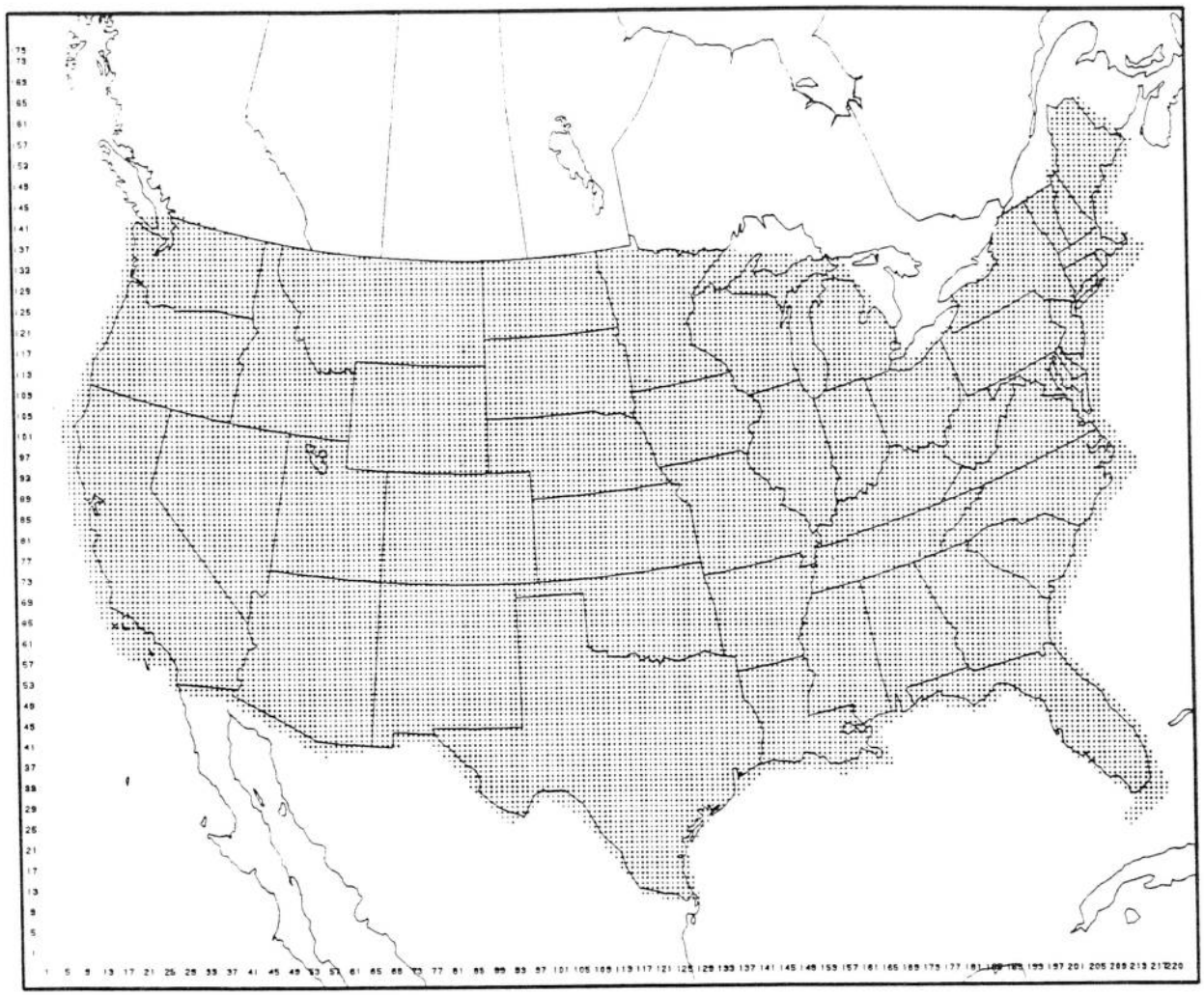

Figure 1. QPF predictor/predictand grid. The analysis grid is a 175x220 rectangular array whose full extent is indicated by coordinate labelling along the leftmost column and the bottom row. The subset of the grid, comprised of 19,636 points, that falls over the 48 states is shown.

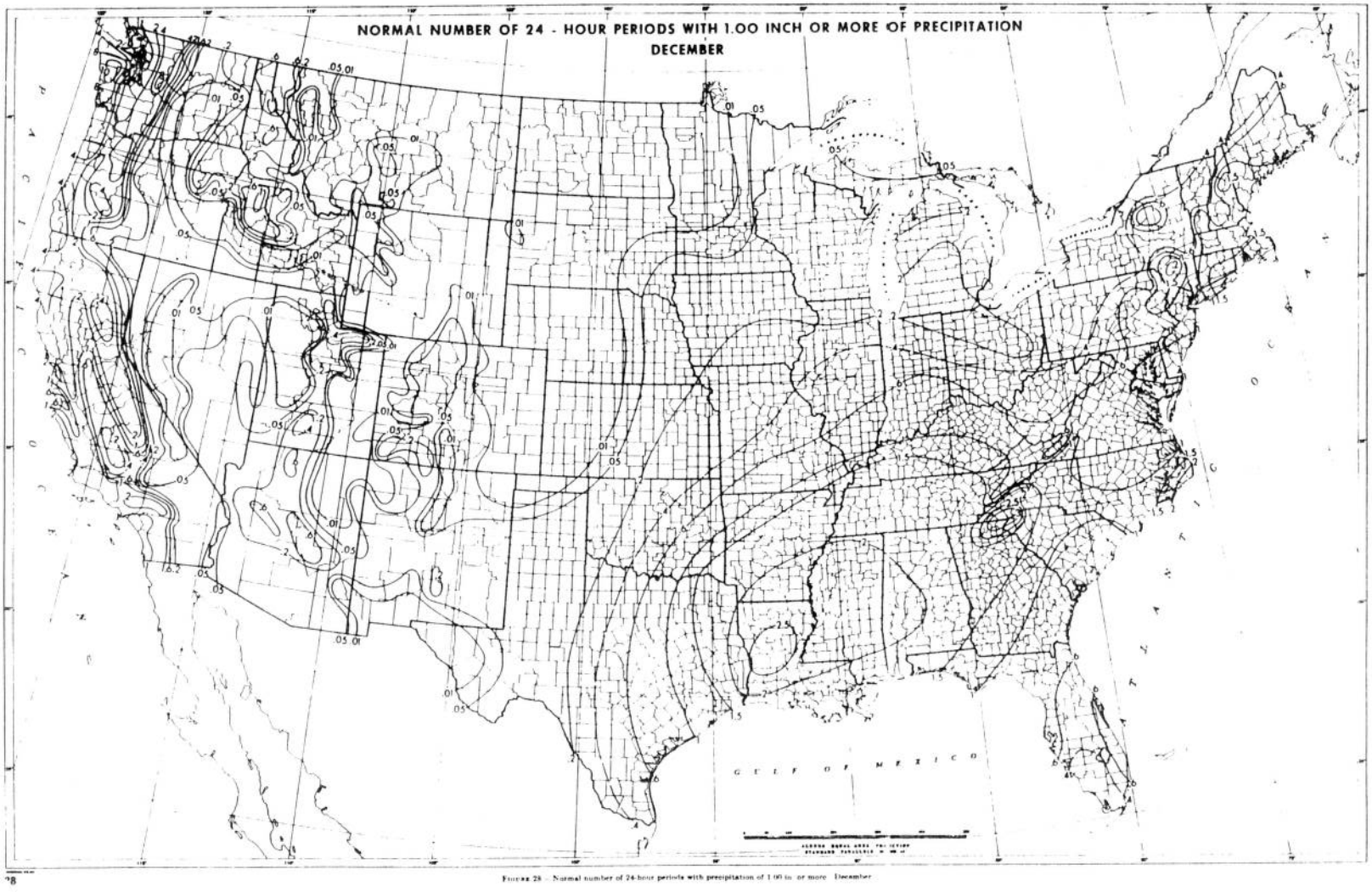

Figure 2. Atlas map of the normal number of 24-h periods with ≥1.00 inches of precipitation during December (taken from Miller and Frederick, 1966).

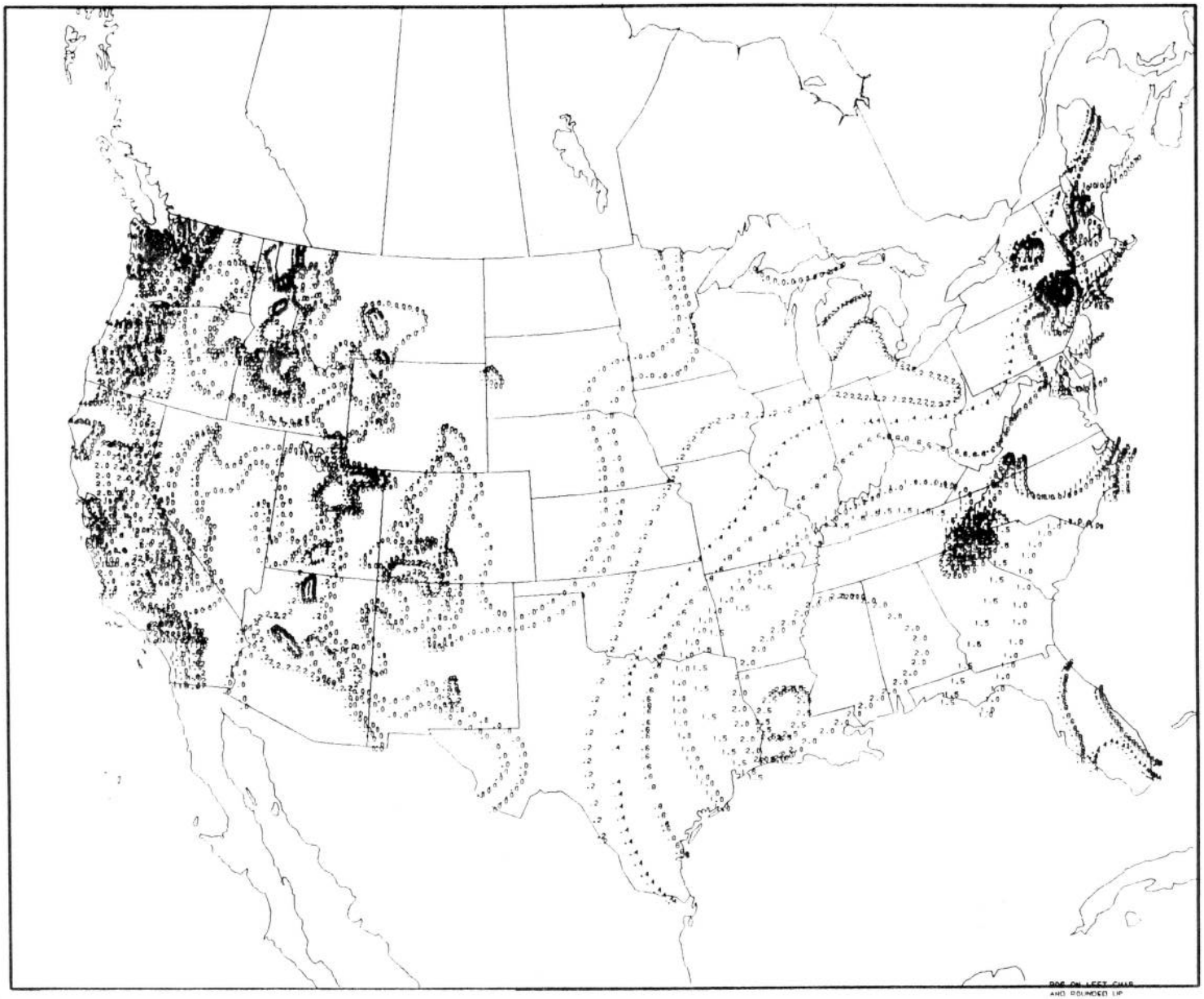

Figure 3. Plot of the digitized contours from Fig. 2. Note that the hundreths digit is not shown.

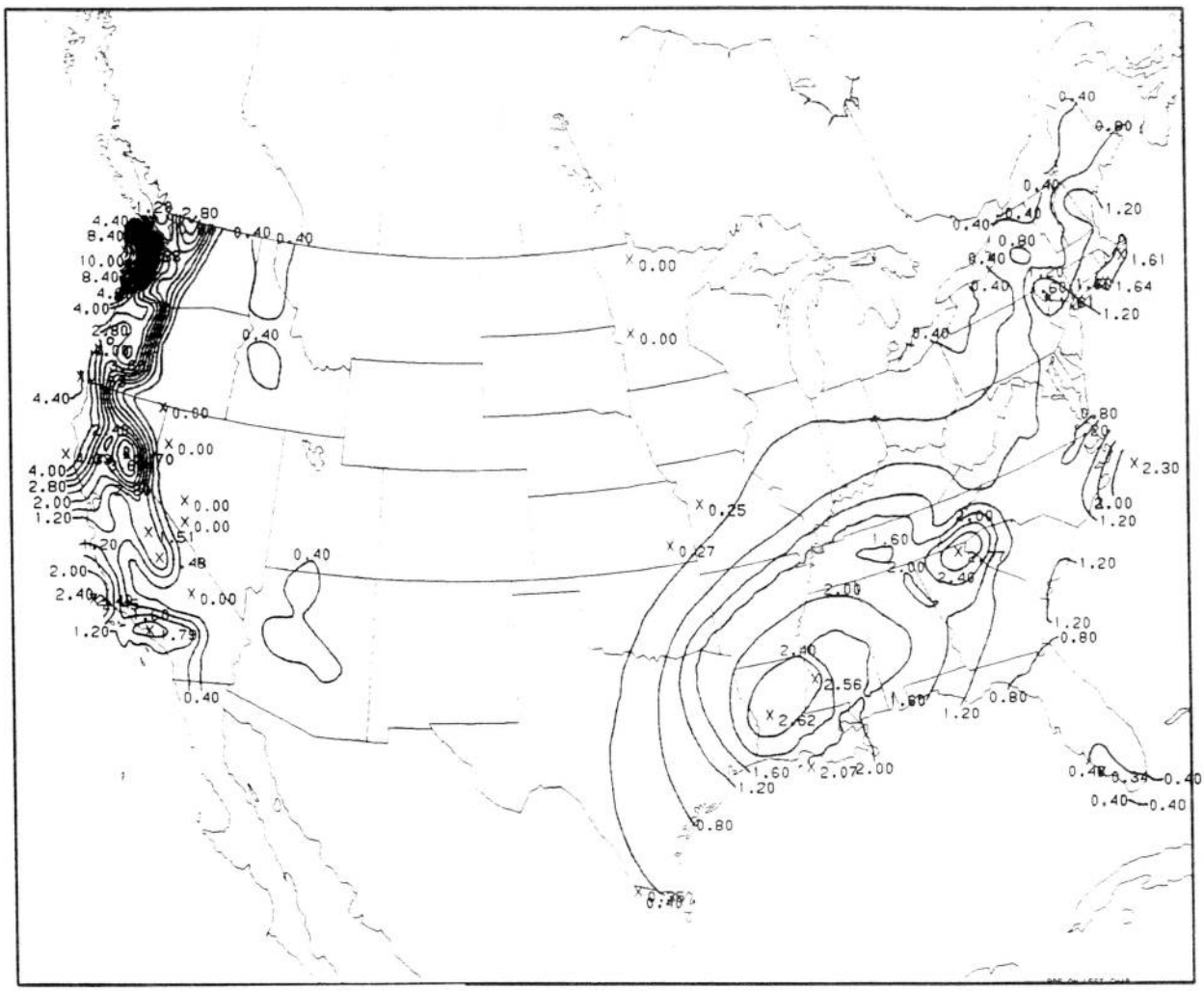

Figure 4. Conventional Cressman objective analysis of the digitized monthly frequency contours for ≥ 1.00 inches during December (see Figs. 2 and 3). Note that the contouring intervals are not the same as those in Fig. 2.

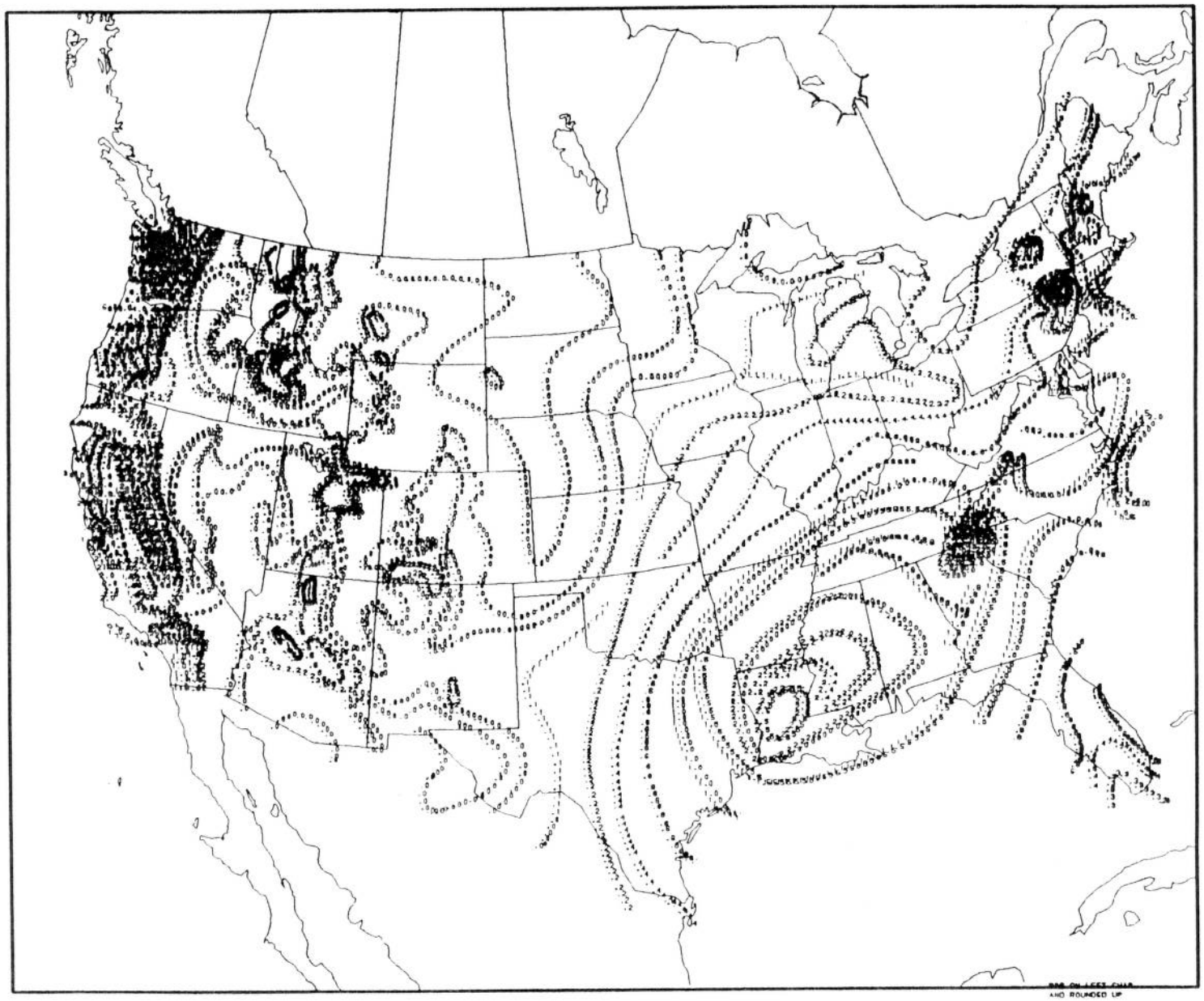

Figure 5. As in Fig. 3 except with inclusion of sketched-in contours and interpolated points.

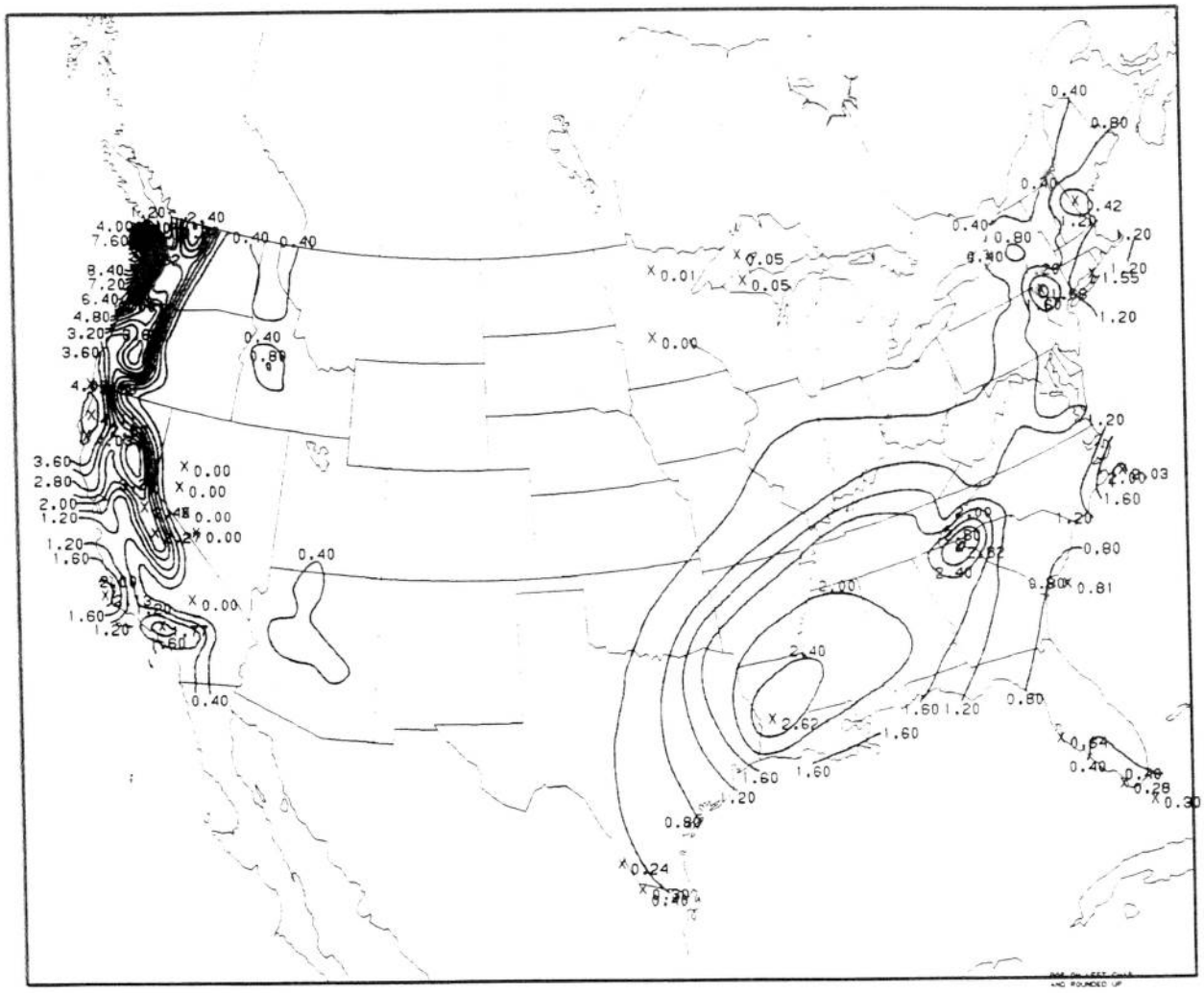

Figure 6. Enhanced analysis of the digitized monthly frequency contours for ≥ 1.00 inches during December. The enhancements consisted of the enhanced digitization (Fig. 5) and the adjustment to the Cressman analysis correction scheme.

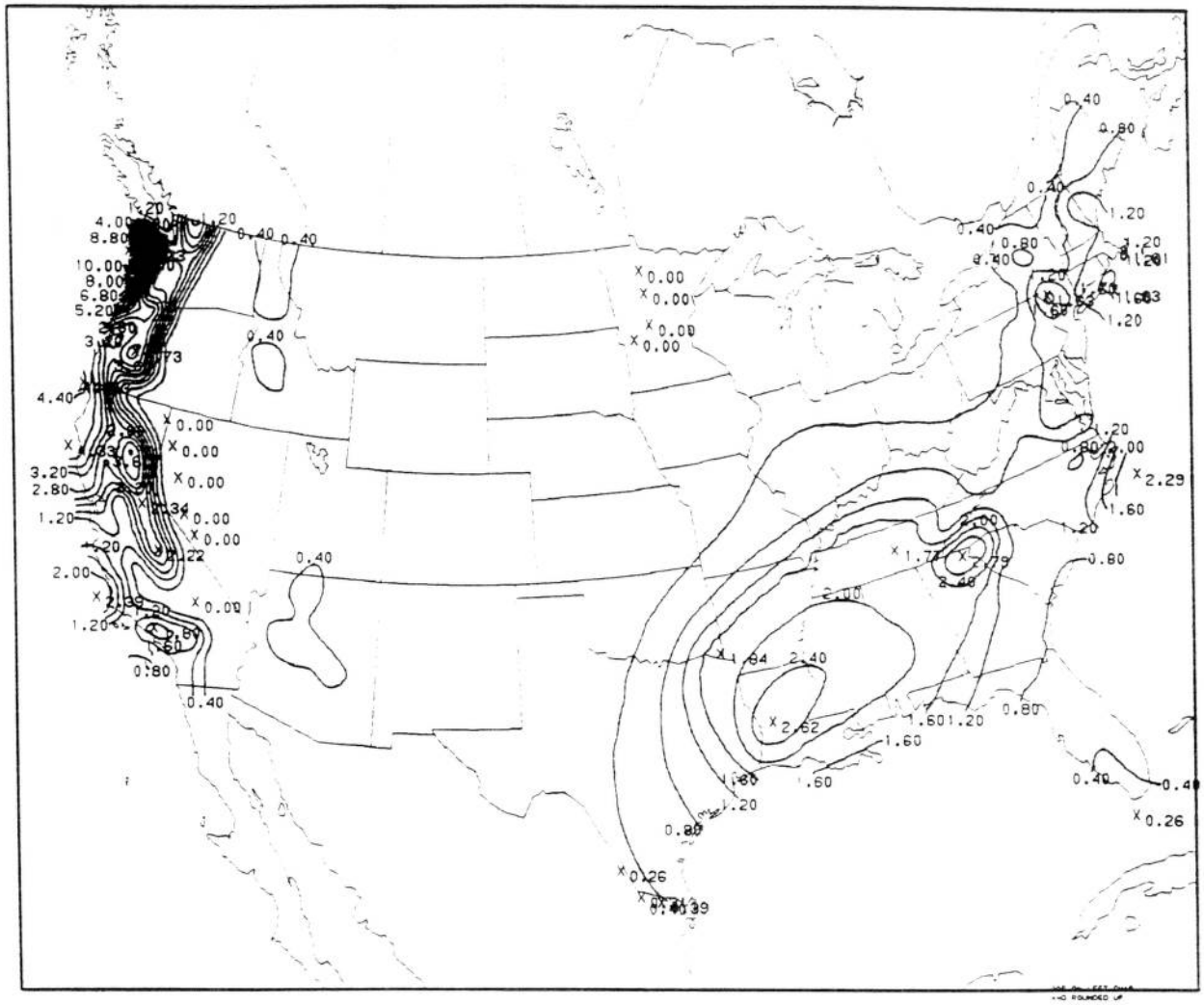

Figure 7. As in Fig. 4 except that sketched-in lines were added to the digitized field (see Figs. 3 and 5). However, the interpolated points included in Fig. 5 were not used.

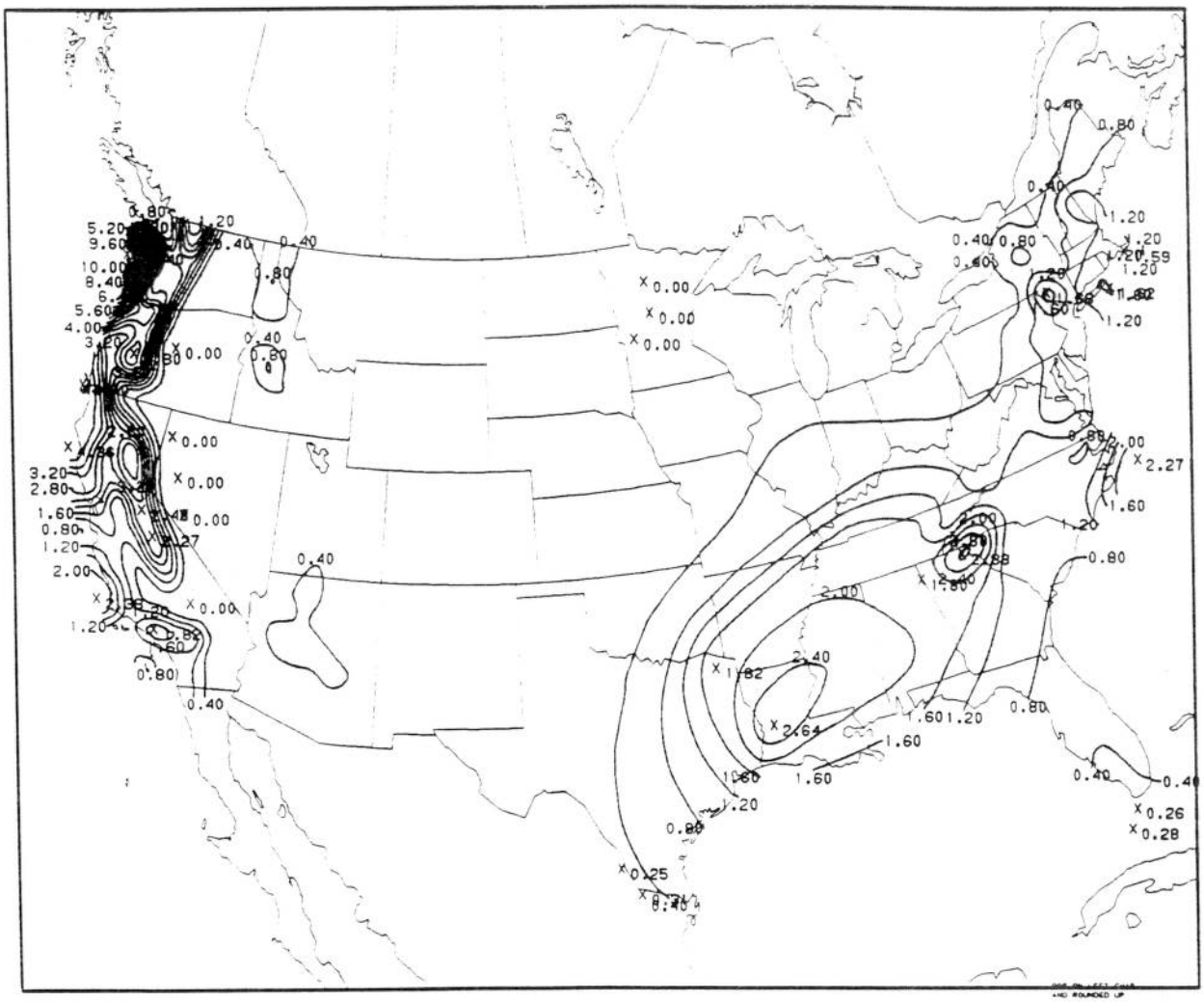

Figure 8. As in Fig. 6 except that the adjustment of Cressman correction scheme was not used.

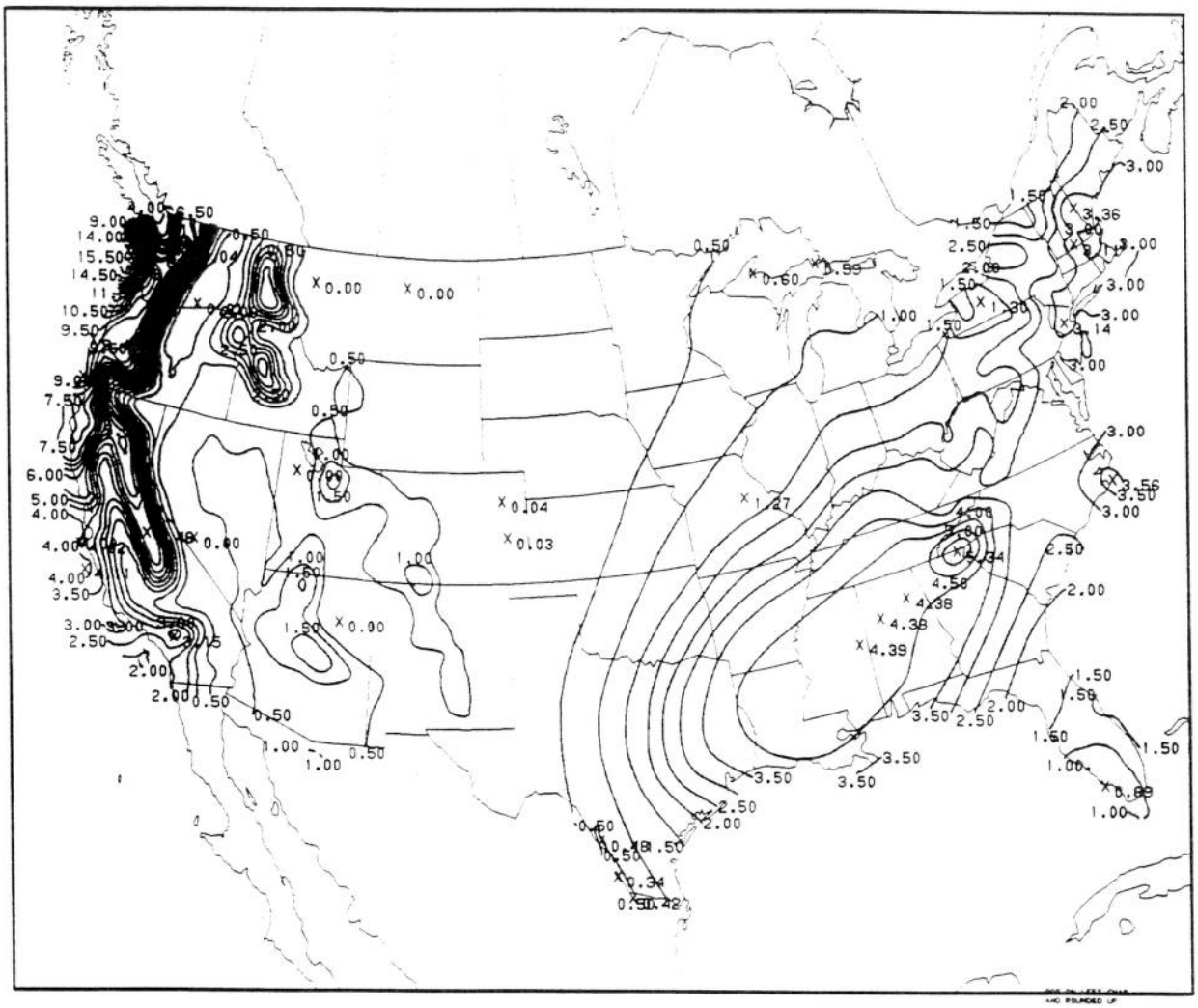

Figure 9. As in Fig. 6 except for ≥0.50 inches.

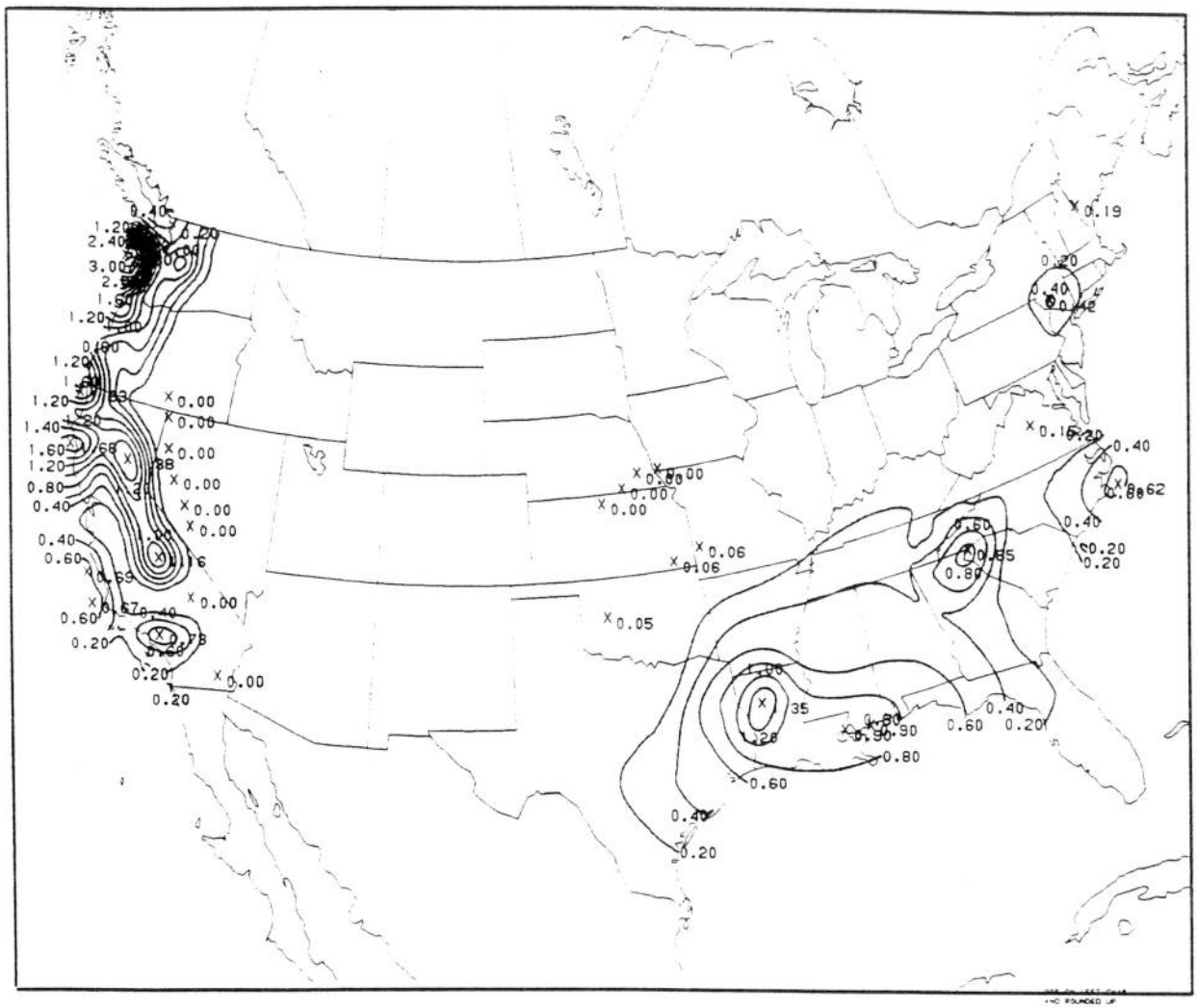

Figure 10. As in Fig. 6 except for ≥2.00 inches